Simulation model of a variable-speed pumped-storage power plant in unstable operating conditions in pumping mode

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Abstract. This paper presents a dynamic simulation model of a laboratory-scale pumped-storage power plant (PSPP) operating in pumping mode with variable speed. The model considers the dynamic behavior of the conduits by means of an elastic water column approach, and synthetically generates both pressure and torque pulsations that reproduce the operation of the hydraulic machine in its instability region. The pressure and torque pulsations are generated each from a different set of sinusoidal functions. These functions were calibrated from the results of a CFD model, which was in turn validated from experimental data. Simulation model results match the numerical results of the CFD model with reasonable accuracy. The pump-turbine model (the functions used to generate pressure and torque pulsations inclusive) was up-scaled by hydraulic similarity according to the design parameters of a real PSPP and included in a dynamic simulation model of the said PSPP. Preliminary conclusions on the impact of unstable operation conditions on the penstock fatigue were obtained by means of a Monte Carlo simulation-based fatigue analysis.

1 Introduction

Variable speed operation offer several advantages for a pump-turbine both in pumping and generating modes such as a) the possibility of an almost instantaneous active power control, b) reactive power control and c) higher efficiency and wider range of operation [1].

However, at part load in pumping mode, reversible pump-turbine machines suffer from unstable behavior related to a strong fluid-dynamical interaction between rotor and stator parts that causes the development of unsteady phenomena, dissipating the fluid energy with a consequent decrease in head. Moreover, if this unstable operating zone is located below the highest operating head, it could prevent the start-up in pumping mode at this head negatively affecting the plant's regulation capacity.

The pressure and torque pulsations associated with these unsteady phenomena might propagate both along the power plant conduits and to the electrical grid. The propagation of pressure pulsations might cause fatigue in the penstock and, as a consequence, reduce the power plant lifetime or require a higher investment. The torque pulsations might in turn have a certain influence on the power quality and, as a consequence, affect the design and cost of the converter filters.

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The material fatigue is a phenomenon of extreme importance as regards the reliability and safety of various types of engineering structures and is recognized as one of the major causes of destruction of materials [2]. However, to the authors' knowledge, no previous paper has evaluated whether or not the pressure pulsations that develop at part load in pumping mode cause a significant fatigue in the penstock. In [3], the authors evaluated the risk of fatigue in the penstock of a specific hydropower plant due to the tracking of the secondary load-frequency control set-point signals, and concluded that the secondary load-frequency control do not cause a significant fatigue with a proper set of turbine governor parameters. As the authors stated in the paper, fast hydraulic transient phenomena such as those related to the pump-turbine start-up and shutdown, fast mode change, etc., were not considered in the study.

The objective of this paper is twofold: to propose and experimentally validate a set of functions to model the pressure and torque pulsations that develop in a pump-turbine operating at part load in pumping mode; to preliminary evaluate the impact of the propagation of the pressure pulsations along the power plant conduits on the penstock fatigue. The pursued objective can be of special interest for existing pumped storage power plants (PSPP) which, maintaining the existing pump turbine runner, will be upgraded to variable speed, as is the case in some PSPP recently analysed in the eStorage European project [4]. The main reason for such an upgrade is that, as demonstrated in [5], the variable speed technology allows the PSPP to participate in the restoration reserve services in pumping mode and therefore to increase its revenue.

For the purposes mentioned above, both detailed numerical and experimental analyses have been carried out on a reversible pump-turbine by Dep. Industrial Engineering – University of Padova.

A dynamic simulation model of the laboratory-scale PSPP has been developed. The model considers the dynamic behavior of the power plant conduits taking into account the water hammer effects, as well as the pump-turbine operating as a variable speed pump. The pump-turbine operation curves (head-flow-rotation speed and torque-flow-rotation speed) have been obtained from the CFD model results. The model synthetically generates both pressure and torque pulsations that reproduce the operation of the pump-turbine in its instability region by means of a set of sinusoidal functions. These sinusoidal functions have been properly calibrated from the results of a spectral analysis of the pressure and torque signals provided by the CFD model. The results of the simulation model match the numerical results of the CFD model with reasonable accuracy.

The pump-turbine operation curves and the functions used to generate pressure and torque pulsations have been up-scaled according to the design parameters of a real PSPP, and then incorporated in a dynamic simulation model of the said plant. Preliminary conclusions have been obtained on the impact of the pump-turbine unstable operation conditions on the risk of fatigue of the penstock by means of a Monte Carlo simulation based fatigue analysis.

2 CFD model validation

Numerical analyses were carried out by the commercial software ANSYS 15.0 on the first stage of a two stages reversible pump-turbine in pump-operating mode (Figure 1). In order to validate the accuracy of the numerical simulations, the experimental data obtained according to ISO standards from Dep. Industrial Engineering – University of Padova was compared with steady simulations, carried out for some operating points at a constant rotation speed of 600 rpm. The comparison in terms of head is reported in Figure 2.

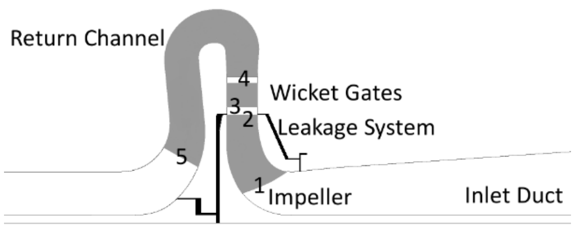

Figure 1. Meridional view of the numerical model. Regions filled in grey refer to the blades; region filled in black refers to the leakage system

The maximum percentage error of -3.84% in head between the experiment and simulation was observed just before the hump-type instability zone. The head showed a tendency to smaller prediction than the experimental data at the BEP (-1.49%) and a tendency to a greater prediction in the hump type instability zone (max +1.24%). The errors may be arising from the practical limitations in numerical model but all the errors between the simulation and experiment are in a reasonable range not only at BEP condition.

3 CFD simulations

To study the evolution of the flow field in a dynamic power reduction scenario the wicket vane was fixed at 18° and kept constant during the simulation. The transient numerical simulation on the entire machine was carried out with a time-varying boundary condition in which the impeller speed was reduced every time step whereas the total pressure at inlet and the average static pressure at outlet were varied according to the experimental values obtained at steady conditions. The initialization was based on the results of the steady simulation carried out for the BEP flow rate and a simple linear variation of the impeller speed from 100% to 88% was fixed (Figure 2). To obtain the variation of pressure in the transient process, monitoring points were created in the whole pump-turbine model.

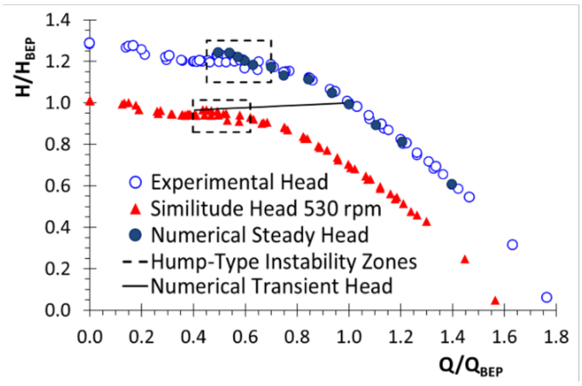

Figure 2. Comparison between numerical and experimental head curves.

The numerical analyses captured the development of unsteady phenomena in the stators affecting the pressure distribution on the vanes, thereby modifying their load distribution and inducing dynamic load on the shear pin or the guide vanes stem.

Spectral analyses in frequency and in time-frequency domain were carried out to characterize the unsteady phenomena and the frequency content of the numerical signals. These signal were acquired at each time step during the whole simulation of power reduction. Time step was determined by using a Hamming window in the Lomb periodogram. More details about the results of the numerical analyses can be found in [6].

4 Laboratory plant simulation model

The main purpose of the laboratory plant simulation model is to reproduce the above described CFD simulation. The model considers the water and pipe elasticity in the suction pipe by means of an approach similar to the one used in [7]. Due to the short length of the impulse pipe, it has been modeled using a rigid water column approach. The flow-head loss function has been obtained by linear regression from the results of the CFD simulations. Upper tank dynamics is considered due to its reduced size.

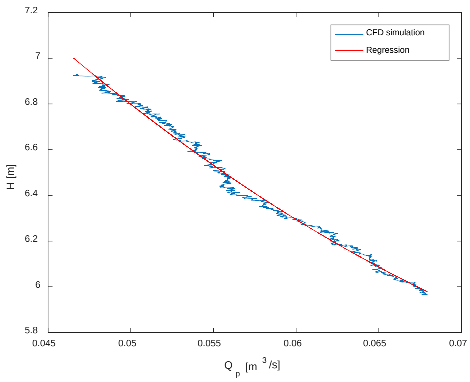

Figure 3. Head-flow operation curve for n=558 rpm.

The pump-turbine has been modeled through its operation curves (head-flow-rotation speed and torque-flow-rotation speed) and a couple of functions that synthetically generate pressure H* and torque C* pulsations (1)-(2). The parameters of the pump-turbine curves corresponding to *n*=558 rpm were obtained by linear regression from the results of the CFD simulation (see Figure 3). The parameters corresponding to other rotation speeds were then obtained by hydraulic similarity from the previous ones.

The amplitude $A_{H,p}$, $A_{C,p}$ and frequency $f_{H,p}$, $f_{C,p}$ parameters in (1) and (2) have been calibrated from the results of the spectral analysis carried out on the results of the CFD simulation. As can be seen from Figure 4 the power spectrum of pressure pulsations corresponding to both the CFD simulation and the sinusoidal function match significantly with each other. In order to harmonize and plot the results of the spectral analysis, frequency values have been formulated in terms of Strouhal number, S_t [6].

$$H^*(n,t) = \sum_{p=1}^{6} A_{H,p}(n) \cdot sin\big(2\pi \cdot f_{H,p}(n) \cdot t\big) \tag{1}$$

$$C^*(n,t) = \sum_{p=1}^{8} A_{C,p}(n) \cdot sin\big(2\pi \cdot f_{C,p}(n) \cdot t\big) \tag{2}$$

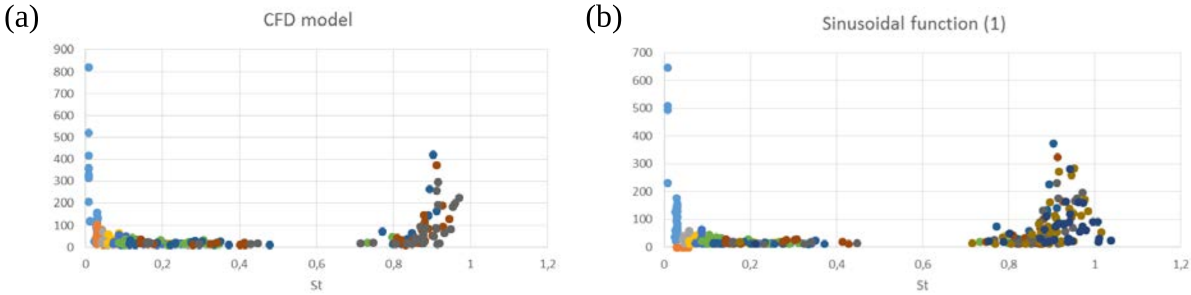

Figure 4. Power spectrum of pressure pulsations corresponding to (a) the CFD simulation and (b) sinusoidal function (1).

The CFD simulation has been reproduced in the simulation model for validation purposes. Figure 5 shows the pump flow and head obtained in both models. As can be seen in the figure, the dynamic simulation model properly reproduces the behavior of the laboratory plant in unstable operating conditions.

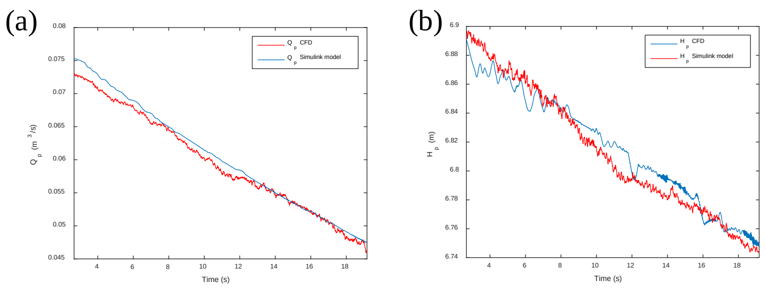

Figure 5. (a) Flow and (b) Head comparison between CFD and Simulink model.

5 Pumped-storage plant simulation model

The pump-turbine operation curves and the sinusoidal functions used to model the pressure and torque pulsations have been up-scaled by hydraulic similarity [8] and incorporated in a dynamic simulation model of a real PSPP. The PSPP considered (Net head=500m, flow = 44,29 m^3/s per unit) consists of two pump-turbines and a single long penstock. Each pump-turbine is connected to the penstock through a short connection pipe. The PSPP upper reservoir is large enough to neglect its level variation.

Because one of the paper objectives is to evaluate the impact of the propagation of pressure pulsations along the PSPP conduits on the risk of penstock fatigue, both the connection pipes and the penstock have been modeled by the characteristic method [9].

In order to study if the propagation of pressure pulsations along the power plant penstock could cause damage due to fatigue phenomenon, a Monte Carlo simulation has been carried out considering a random lag or lead between the positions of the two pump-turbines. For each simulation, a set of tangential stresses is obtained in the most critical penstock section –union between the penstock and the connection pipes- as a function of the pressure amplitude $\Delta\sigma_c = f(\Delta p)$ [3,10]. A single equivalent stress is then obtained for each simulation by using the expression proposed in [2]. Next, a weighted equivalent stress is calculated for all simulations. According to [11], the weighted equivalent stress would cause no lifetime reduction for fatigue reasons (13,89 MPa < 14,57 MPa). However, pressure pulsations, and consequently $\Delta\sigma_c$, are related to PSPP net head. Thus, it would be possible to find fatigue damages in a PSPP with a higher net head.

6 Conclusions

A dynamic simulation model of a variable-speed laboratory pumped-storage power plant operating in unstable operating conditions in pumping mode has been developed. The model has been calibrated from the results of a CFD simulation. The CFD model has been in turn validated from an experiment carried out in the laboratory plant.

The pressure and torque pulsations that develop in the pump-turbine impeller have been modeled through a couple of sinusoidal functions. These functions have been calibrated from the results of a spectral analysis carried out on the results of the CFD simulation.

The dynamic simulation model reproduces the results of the CFD simulation with a reasonable accuracy.

The pump-turbine model has been up-scaled according to the design parameters of a real pumped-storage power plant and has been incorporated in a dynamic simulation model of the said power plant. The simulation model has been used to evaluate the impact of the unstable operating conditions in pumping mode on the risk of penstock fatigue. The results of the fatigue analysis show that the risk of penstock fatigue is negligible. Further research is necessary to evaluate the impact of unstable operating conditions in pumping mode in other pumped-storage power plants with higher heads, where unstable operating conditions might have a greater impact.

7 References

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